Exploring Techniques for Improving Retrievals of Bio-optical Properties of Coastal Waters

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LONG-TERM GOALS

Development of algorithms for improved retrievals and monitoring of inherent water optical properties (IOP) from satellite imagery of coastal waters with current and future sensors for improvement of Navy electro-optical system performance utilizing: 1) VIS-NIR channels, 2) polarization characteristics of light in sea water and 3) advanced atmospheric correction schemes.

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OBJECTIVES

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of VIS and NIR bands through: a) the use of reflectance characteristics obtained from red-NIR measurements as additional constraints in basic inversion models, b) utilization of satellite data (SeaWiFS, MODIS, MERIS, etc.) and the data from the LISCO offshore platform.

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of in-water visibility by particle type discrimination, and algorithm development through: a) the simulation of polarization components of reflectance for coastal water environments using polarized radiative transfer and b) measurements of polarization characteristics in field conditions to validate radiative transfer modeling and assess possibilities for the separation of organic and inorganic particulate components, improvement of underwater visibility and target detection.

Development of advanced atmospheric correction models including a) incorporation of additional constraint for atmospheric correction in coastal waters, b) development of the interface to perform retrievals based on real time radiometer and lidar observations.

APPROACH

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of VIS and NIR bands The data from the Long Island Sound Coastal Observatory (LISCO) from both the multispectral SeaPRISM and hyperspectral HyperSAS, installed for the validation of current and future Ocean Color satellites, is analyzed in terms of minimizing impacts of sun and sky glint on measured water leaving radiance. Three neural networks (NN) for reflectances related to IOPs, and simulated by Hydrolight for a broad range of water conditions, were trained to retrieve water components and compared with NOMAD and field CCNY data. Simulated datasets were also used to develop a BRDF model for coastal waters and to validate these on the LISCO data and its comparison with MODIS satellite imagery.

Utilization of under and above water polarization components of reflectance spectra for improvement of in-water visibility by particle type discrimination and algorithm development Polarization characteristics measured in the open ocean using our multi-angular hyperspectral polarimeter were compared with Monte Carlo simulations (Kattawar's group). Polarimetric measurements and simulations were also used to develop novel techniques for the retrieval of the index of refraction and the slope of the particle size distribution, underwater degree of polarization (DOP) from above water measurements, attenuation coefficient and fluorescence component. Modification of the polarimetric instrumentation was done to extend capabilities of polarization radiometric measurements and imaging.

Development of advanced atmospheric correction models Combinations of instrumentation on the LISCO site measuring aerosol properties (SeaPRISM) and polarized reflectances (HyperSAS) were utilized for the polarized correction of the sky glint and accurate retrieval of below surface DOP from above water observations with polarization sensitive radiometers.

WORK COMPLETED

- The Long Island Sound Coastal Observatory (LISCO) on an offshore platform, operational since the fall 2009 as a part of NASA AERONET and AERONET-OC networks combining multispectral SeaPRISM and hyperspectral HyperSAS instruments, evolved into one of the key elements for validation of OC satellite data, especially for the planned launch of the JPSS – VIIRS instrument. Quality of the data is continuously evaluated through matchups between instruments on the platform as well as with the satellite data of SeaWiFS, MODIS and MERIS. The data were also used in the validation of the HICO instrument on the International Space Station.

- Three neural networks of remote sensing reflectances for MODIS VIS and NIR bands, and related to IOP components, were trained on synthetic data and validated on the NOMAD and field CCNY data, and showed good performance for IOP retrievals over a very broad range of water parameters.

- Based on synthetic datasets, a BRDF model was developed for coastal waters, and validated on the data of the two LISCO instruments, and its comparison with MODIS satellite imagery.

- A coastal ocean circulation model (FVCOM) was set up for regions ranging from the Chesapeake Bay to Long Island Sound, and was calibrated against data at a number of NOAA, USGS, etc observation stations. The model will be used for further incorporation of the satellite data.

- Polarization characteristics measured in the open ocean, with the multi-angular hyperspectral polarimeter, were compared with Monte Carlo radiative transfer simulations (G. Kattawar's group) showing excellent matches for various viewing and water conditions (also part of the MURI program – PI M. Cummings, see details in the MURI report).

- A new technique was developed for the retrieval of the index of refraction and the size distribution slope of particles, based on the polarimetric measurements (also part of the MURI program – PI M. Cummings, see details in the MURI report).

- Techniques were developed and proposed for the retrieval of the underwater degree of polarization (DOP), attenuation coefficient, and fluorescence component from the above water polarimetric measurements.

- Our multi-angular hyperspectral polarimeter was integrated with underwater thrusters for the automated control of azimuth angles at arbitrary depths, and with a newly acquired full Stokes vector imaging camera in an underwater housing, for advanced interpretation of the polarization signatures of naval targets, and the goal of improving visibility and detection.

- The representativeness of our LISCO site for satellite validation activities was demonstrated based on MODIS satellite imagery for different modalities of the atmospheric correction procedures. Aerosol characteristics obtained from the SeaPRISM instrument on the LISCO site were used for the polarized correction of sky glint and for accurate retrieval of below surface DOP from above water observations with polarization sensitive radiometers on LISCO.

RESULTS

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of VIS and NIR bands

Validation of the satellite imagery using LISCO data

To support present and future multi- and hyper-spectral calibration/validation activities, as well as the development of new measurement and retrieval techniques and algorithms for coastal waters, City College (CCNY) along with Naval Research Laboratory at Stennis Space Center, has established an off-shore platform, the Long Island Sound Coastal Observatory (LISCO) which is in operation since October 2009. This site combines multi-spectral (SeaPRISM) and hyperspectral (HyperSAS) radiometer measurements, for comparisons with satellite and in situ measurements and radiative transfer simulations for coastal waters, helping to provide more effective closure for the whole measurement validation/ simulation loop. Thus, measurements from the platform are utilized for multi-spectral calibration/validation of current Ocean Color satellites (MERIS, MODIS, SeaWIFS) in coastal waters. They will be used for evaluating future satellites missions (JPSS-VIIRS) with extension to hyperspectral validations of the hyperspectral sensors (HICO), as well as for improvements in coastal IOP retrieval and atmospheric correction algorithms.

Special procedures were established for filtering HyperSAS data to make it comparable with the SeaPRISM data filtered in accordance with NASA AERONET – OC methodology. The time series of the data for two instruments is shown in Fig. 1.

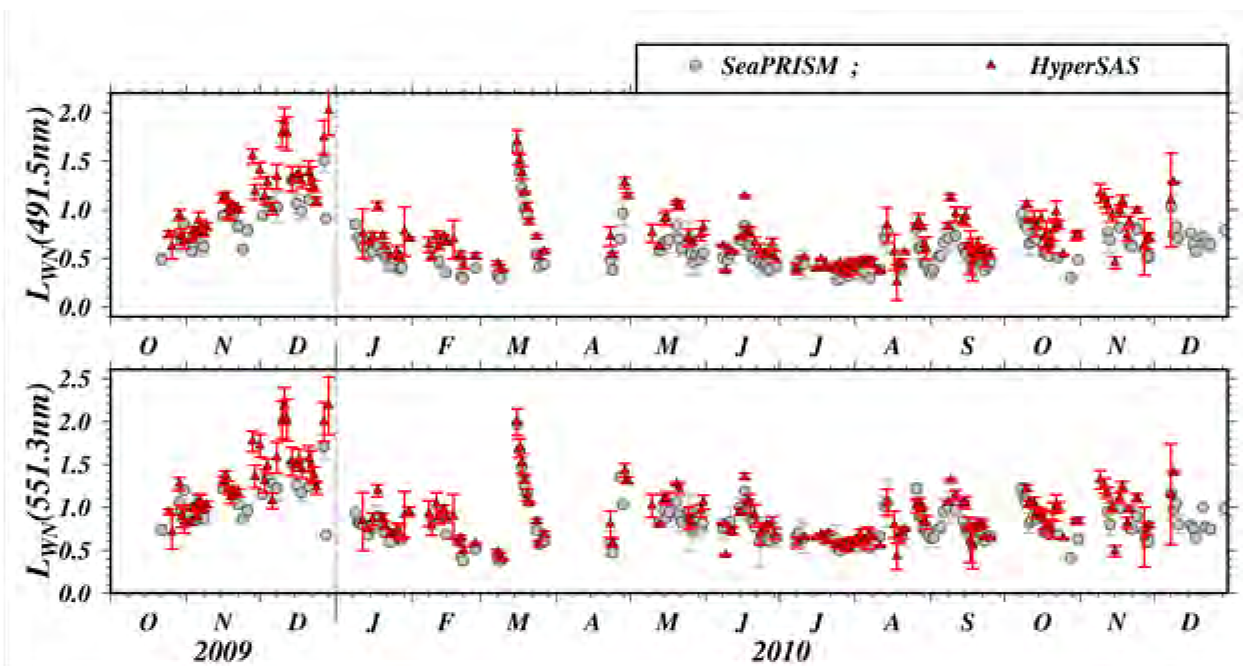

Fig. 1. Time series of daily average of the exact normalized water-leaving radiance (in mW cm^{-2} sr^{-1} nm^{-1}) retrieved with HyperSAS (red triangles) and SeaPRISM (grey circles) for two SeaPRISM bands centered on 551 and 491 nm. The vertical bars correspond to the daily standard deviations.

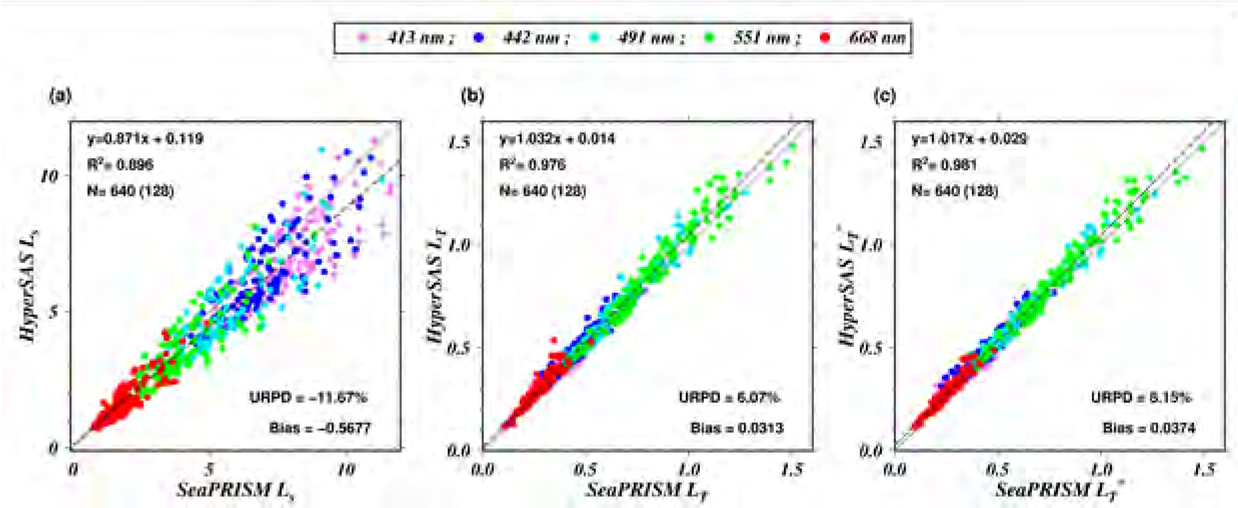

Fig. 2. Intercomparisons of HyperSAS and SeaPRISM direct measurements (in mW cm^{-2} sr^{-1} nm^{-1}) of (a) sky radiance L_s, (b) total sea radiance L_T and (c) the lowest sea radiance values of each measurement sequence L_T^*. N is the total number of the comparison, the bracketed value is the number of different measurement sequences used in the comparison. The bias is given in radiance unit.

By comparison of the SeaPRISM and HyperSAS data, the total uncertainties in remote sensing reflectances and the contribution of different steps to these from data processing of the measured total radiances are estimated and shown in Fig. 2. The need for improvement of the SeaPRISM model for estimation of atmospheric transmission coefficient is evidenced by its discrepancy (about 5%) with the directly measured atmospheric transmittance as measured by HyperSAS.

Development of a neural network approach to retrieve inherent optical properties of sea water from MODIS observations.

Retrieving inherent optical properties of sea water from remote sensing multispectral reflectance measurements is difficult due to both the complex nature of forward modeling and the inherent nonlinearity of the inverse problem. In our approach, we utilized three neural networks (NNs) in parallel. The first NN is used to relate the remote sensing reflectance at available MODIS visible wavelengths (except the 678 nm fluorescence channel) to the absorption and backscatter coefficients at 442nm (peak of chlorophyll absorption). The second NN separates algal and non-algal absorption components, with the ratio of algal to non-algal absorption as an output. The third NN separates (to our knowledge, for the first time) the non-algal absorption into CDOM and mineral absorption components. The resulting synthetically trained algorithm was tested using both the NASA Bio-Optical Marine Algorithm Data set (NOMAD), as well as our own field data sets from the Chesapeake Bay and Long Island Sound, New York. Very good agreement was obtained, with R^2 values of 93.75%, 90.67% and 86.43% for the total, algal and non-algal absorption respectively for the NOMAD dataset. For our field data, which covers waters with absorptions of up to about 6m-1, R^2 is 91.87% for the total measured absorption. Examples of inversions are shown in Fig. 3.

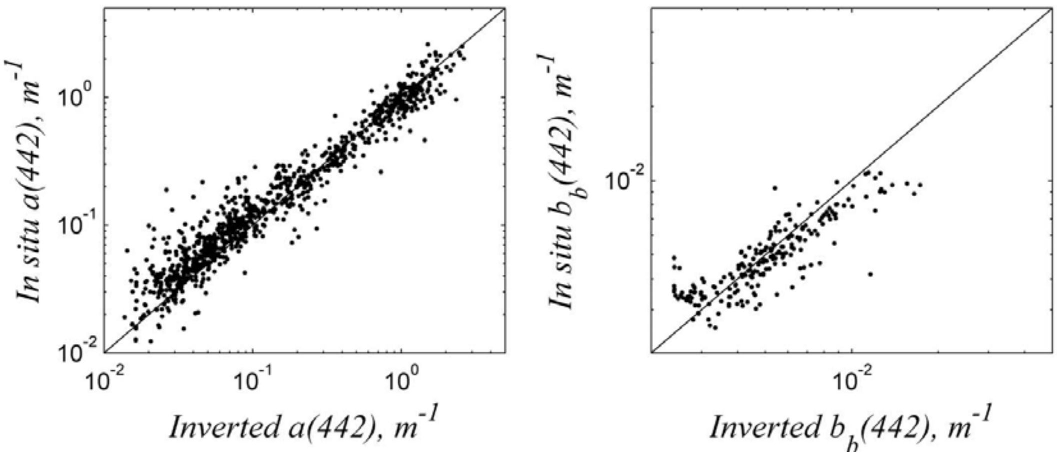

Fig. 3. Inverted IOP from the neural network (x-axis) plotted against the in situ values from the NOMAD dataset for a(442) m^{-1} and b_b(442) m^{-1}

Assessment of the Bidirectional Reflectance Correction of Above-water and Satellite Water-leaving Radiance in Coastal Waters

The current operational algorithm for the correction of bidirectional effects for the satellite ocean color data is optimized for typical oceanic waters and generally is not applicable to coastal waters. In order to analyze the bidirectional reflectance distribution function (BRDF) for coastal waters, a dataset of typical remote sensing reflectances was generated through radiative transfer simulations for a large range of viewing and illumination geometries. Based on this simulated dataset, a coastal water focused remote sensing reflectance model is proposed to correct above-water and satellite water leaving radiance data for bidirectional effects. The proposed model was validated with a one year time series of *in situ* above-water measurements acquired by collocated multi- and hyperspectral radiometers, which have different viewing geometries, installed at the Long Island Sound Coastal Observatory (LISCO). Match-ups and intercomparisons of concurrent measurements with these instruments show that the proposed algorithm outperforms the currently used algorithm at all wavelengths, with an average improvement of 2.4%. LISCO's time series data has also been used to evaluate improvements in the match-up comparisons of MODIS satellite data when the proposed BRDF correction is used in lieu of the current algorithm. This showed that discrepancies between coincident in-situ sea-based and satellite data were decreased by 3.15% with the proposed algorithm. Comparison of performance of the current (Morel-Gentili-MG) and the proposed algorithm on the synthetic data is shown in Fig. 4.

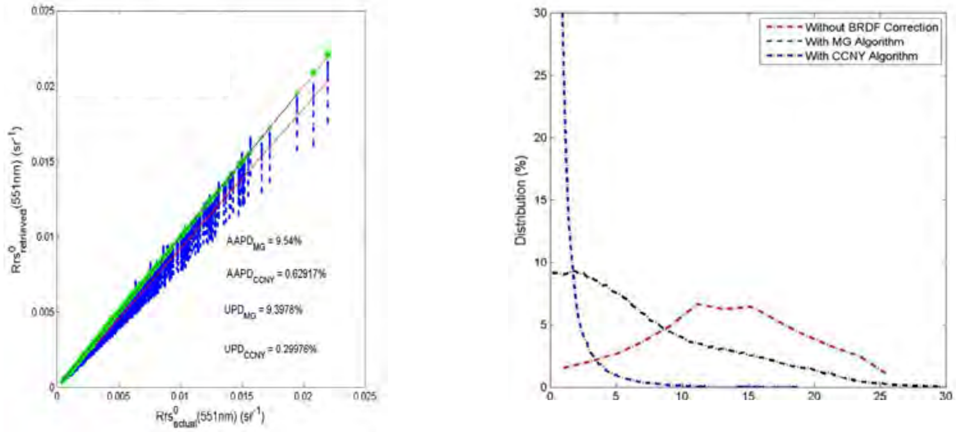

Fig. 4. Comparisons between Rrs^0_{actual} and $Rrs^0_{retrieved}$ derived with MG (green dots) and with CCNY (blue dots) algorithms for $\theta_v = 40^o$, $20^o \leq \theta_s \leq 70^o$ and $60^o \leq \phi \leq 180^o$ at (a) 551. Regression line between $Rrs^0_{retrieved(MG)}$ and Rrs^0_{actual} is shown in red and that of $Rrs^0_{retrieved(CCNY)}$ is shown in black. (b) Distribution of the absolute percent difference, δ, values between Rrs^0_{actual} and Rrs without BRDF correction (red), $Rrs^0_{retrieved(MG)}$ (black) and $Rrs^0_{retrieved(CCNY)}$ (blue) for each matchup.

Hydrodynamic model for Chesapeake Bay - Long Island Sound area

A coastal ocean circulation model (FVCOM) was set up for regions ranging from the Chesapeake Bay to Long Island Sound, and was calibrated against data at a number of NOAA, USGS, etc observation stations. A finer model mesh is employed next to coastlines, to achieve high-resolution prediction of coastal processes (less than 50 m along all coastlines on the NJ seashore and south banks of Long Island Sound). In addition, model development with two-way coupling between FVCOM and CFD and other models was used to predict multi-scale and multi-physics problems. On this basis, investigations were applied to various emerging problems including: a) tidal energy distributions along coastlines; b) 3D thermal plume discharged from diffusers at ocean bottom; c) coastal flooding for projected storm and sea level rise conditions.

Utilization of underwater and above water polarization components of reflectance spectra for improved retrievals of particle type discrimination and algorithm development

Estimation of the attenuation coefficient of the water body using polarimetric observations

The degree of polarization (DOP) of the underwater light field in oceanic waters is related to the single scattering albedo (SSA) of suspended particles, which is given by the ratio of the scattering coefficient to the attenuation coefficient (or 1 – the ratio of the absorption coefficient/attenuation coefficient). Knowledge of the SSA and of the particulate scattering matrix permits solution of the radiative transfer equation for the ocean body. This then opens up the possibility for estimation of attenuation coefficients from measurements of the Stokes components of the upwelling underwater light field,

which is not possible from unpolarized measurements of the remote sensing reflectance. Using radiative transfer codes (RayXP, Zege et al.) we simulated multiple underwater polarized light fields, with the objective of obtaining a parameterization of this relationship for different viewing geometries (different solar and zenith/azimuth viewing angles) under various water conditions (i.e. various IOPs). It was shown that for viewing angles of about 30º (~40º in the air) there is a good correlation between absorption/attenuation ratio and DOP as can be seen in Fig. 5.

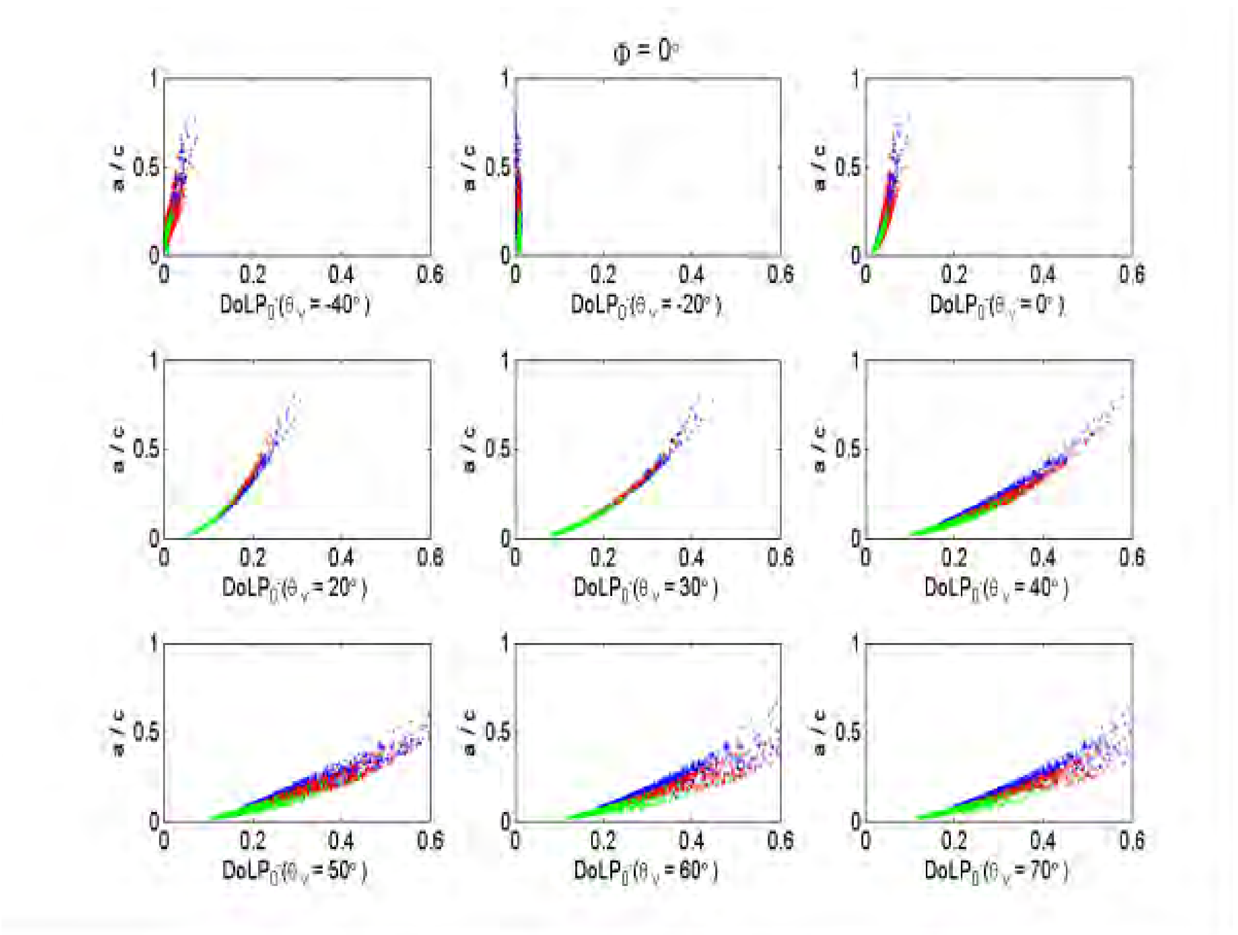

Fig. 5. The relation between a/c and the DoLP just below the ocean surface in the main plane. Blue points correspond to values at 440 nm, green points to 555 nm and red points to 665 nm.

Measurement of water-leaving polarization using above-water hyperspectral instrumentation

A new sky glint correction scheme has been developed in which the aerosol properties retrieved by the standard inversion algorithm of the AERONET system are used to simulate the polarized sky glint radiation. Thus, above and below surface water-leaving polarization fields are retrieved from the above-water polarization measurement. To implement this, two radiance sensors with polarizers oriented vertically and at 45º and looking down at 40º, were added to the HyperSAS radiometer on the LISCO platform in June 2010. In Fig. 6 hyperspectral the DOP determined by this procedure just

below the surface is compared with the fitted spectrum of absorption/attenuation ratio: $DOP_{sim}(\lambda) = p\left(\frac{a(\lambda)}{c(\lambda)}\right)^{q}$ showing a very good match.

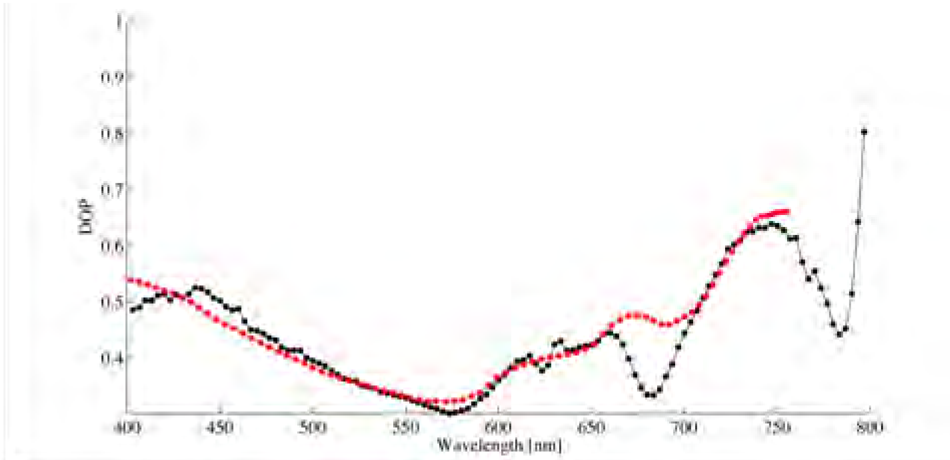

Fig. 6. Spectral degree of polarization (DOP) just below the surface corresponding to the HyperSAS-POL measurements (black line) and to the Timofeeva's parameterization (red line) based on the actual values of the* a *over* c *ratio measured at the LISCO site. The scattering angle is 106° and 126° above and below surface, respectively.

Retrieval of algal fluorescence component from measurements of the underwater DOD

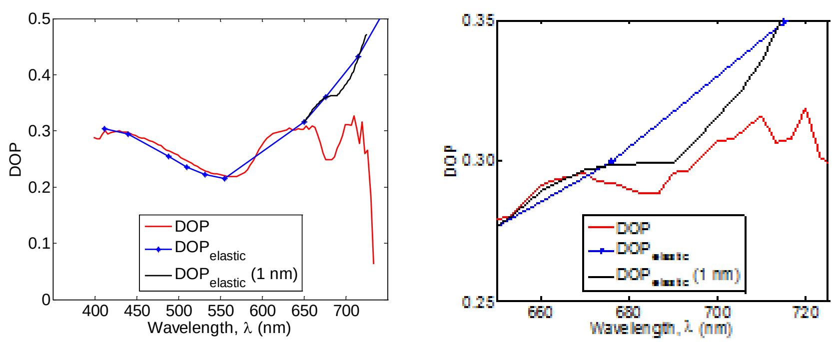

Fig. 7. (a) Spectral behavior of the measured DOP (red) and simulated above surface values transmitted to below surface values (blue) $DOP_{elastic}$ at one of the stations. The blue line represents simulations performed at wavelengths 412, 440, 488, 510, 532, 555, 650, 676, 715 and 750 nm. The black line represents the result of simulations carried out at one nanometer resolution (again, transmitted to below surface values), in the spectral range 650 – 725 nm. (b) Same as (a) but only the wavelength range 650 – 725 nm is considered.

Multiangular hyperspectral measurements of the underwater polarization light field, together with measurements of the inherent optical properties (IOPs) collected in eutrophic waters of the Chesapeake/Virginia and New York Harbor/Hudson River areas showed that chlorophyll a fluorescence markedly impacts (reduces) the underwater degree of polarization (DOP) in the 650 – 700 nm spectral region. By taking note of the unpolarized nature of algal fluorescence and the partially polarized properties of elastic scattering, we are able to separate the chlorophyll a fluorescence signal from the total radiance. The analysis is based on comparisons of experimental measurements with vector and scalar radiative transfer computations (obtained using measured IOPs as inputs). The example of measured and simulated DOP is shown in Fig. 7.

Development of advanced atmospheric correction models

The impact of aerosols on the reflected sky polarization was investigated. The Stokes parameters I, Q and U of the sky radiation reflected by a ruffled sea surface were simulated for different aerosol conditions. Simulations were carried out for two aerosol models: fine and coarse aerosol types, and for aerosol optical thicknesses at 550 nm ranging from 0 to 0.4. The resulting I, Q and U parameters at 550 nm are shown in Fig. 8 for different relative azimuths and solar and viewing zenith angle of 60° and 40°, respectively. For the fine aerosol model, the variation in its optical thickness impacts significantly all the Stokes parameters. This variation is dependent on the viewing geometry as can be seen, for the I parameter, where curves of different geometries intersect each other. The same conclusions are applicable to the coarse aerosol model. The variations induced by changes of aerosol loading are completely different for each of these models. Those different optical behaviors can be discerned in the resulting DOP in Fig. 8.

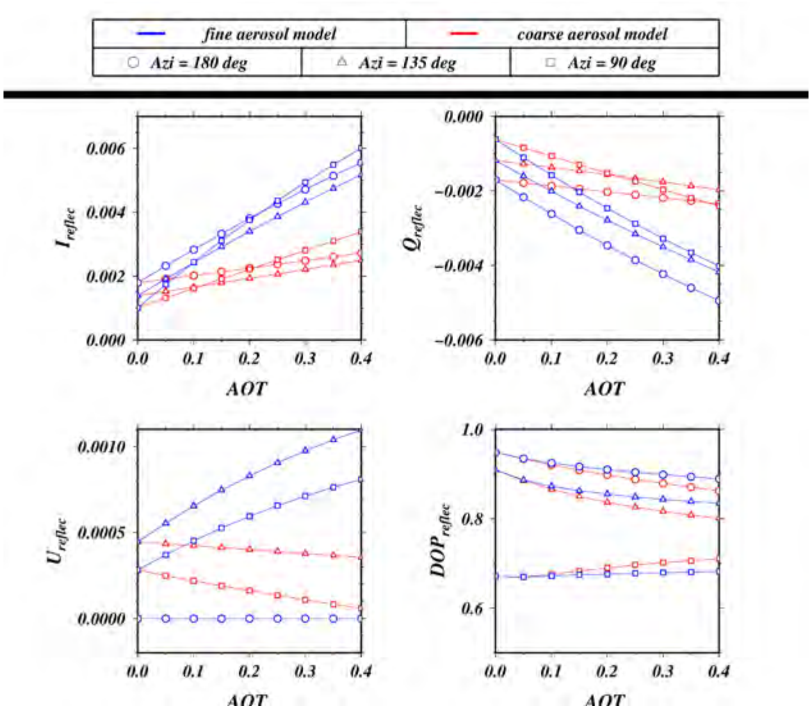

Fig. 8. Sensitivity to aerosol optical thickness (AOT) of the Stokes parameters I, Q and U and the resulting degree of polarization (DOP) of the sky radiation reflected by the sea surface as observed just above the surface.

IMPACT/APPLICATIONS

A new AERONET and AERONET-OC site on the LISCO platform, operational since October 2009 was used continuously for validation of ocean color satellites, water monitoring and algorithm development in coastal waters. The new BRDF model developed by us for coastal waters should now be linked with the current open ocean algorithm for the future satellite applications.

The successful precise measurements of hyperspectral water polarization characteristics below and above water, coupled with the radiative transfer simulations have led to important understandings of the nature and parameters of underwater polarization fields with wide-ranging applications and development of the new techniques for the retrieval of water parameters from near surface and satellite observations by the instruments with polarization sensitive channels. That includes incorporation of information on aerosol characteristics into sky glint correction models for AERONET-OC sites and atmospheric correction for the satellite observations.

RELATED PROJECTS

This ONR project, on improvement of retrieval of bio-optical properties, benefits from the leveraging of funding by NOAA CREST in which remote sensing of coastal waters is an important component.

Starting 2009 the CCNY group also studied polarization characteristics of light in water through another award from ONR N000140911054 for years 2009-2012 with the emphasis on underwater animals vision and camouflage properties and applications.

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